DOCUMENT RESUME

ED 307 161 SE 050 636

TITLE The Ozone Layer. UNEP/GEMS Environment Library No. 2.

INSTITUTION United Nations Environment Programme, Nairobi (Kenya).

PUB DATE 87

NOTE 39p.; For the first issue in this series see SE 050 635. Graphs and drawings may not reproduce well.

PUB TYPE Reports - Descriptive (141)

EDRS PRICE MF01/PC02 Plus Postage.

DESCRIPTORS *Air Pollution; Climate; *Conservation (Environment); Earth Science; *Environmental Education; Environmental Influences; Global Approach; Science and Society; Science Instruction; *Scientific Literacy; World Affairs; World Problems

IDENTIFIERS *Global Environment Monitoring System; *Greenhouse Effect

ABSTRACT

Since the United Nations Environment Program (UNEP) was created, more than a dozen years ago, public understanding of the environmental issues confronting our planet has increased enormously. The Global Environment Monitoring System (GEMS) has provided several environmental assessments. The aim of the UNEP/GEMS Environment Library is to provide authoritative statements, written in plain language, about the major environmental issues the world is now facing. This issue concerns the ozone layer and the possible effects the lessening of this layer will have on the Earth's climate. An overview of the problem is presented followed by a summation of scientific facts and theories to provide a background to the problem. Major topics include: (1) balance of ozone; (2) atmospheric photochemistry; (3) chemical pollution; (4) models of the atmosphere; (5) ozone concentration measurement; and (6) global warming. The future effects on society and the world are investigated with in-depth discussions of the major resulting problems. Lastly, possible ways of dealing with the problem are identified and summarized. (MVL)

****
* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *
****

ED307161

U.S. DEPARTMENT OF EDUCATION
Office of Educational Research and Improvement
EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)

X This document has been reproduced as received from the person or organization originating it.

☐ Minor changes have been made to improve reproduction quality.

• Points of view or opinions stated in this document do not necessarily represent official OERI position or policy.

"PERMISSION TO REPRODUCE THIS MATERIAL HAS BEEN GRANTED BY

Peter Usher

TO THE EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)."

SE 050 436

United Nations Environment Programme
The Ozone Layer
Nairobi, UNEP, 1987
(UNEP/GEMS Environment Library No 2)

Copyright © UNEP 1987
United Nations Environment Programme
PO Box 30552
Nairobi, Kenya

Text and layout: Robin Clarke
Artwork: Oxford Illustrators

The views expressed in this publication are not necessarily those of the United Nations Environment Programme

THE OZONE LAYER

The UNEP/GEMS Environment Library

UNEP's Global Environment Monitoring System (GEMS) now has more than a decade of solid achievement behind it. In that time, we have helped make major environmental assessments of such things as the state of urban air pollution, the greenhouse problem, the rate of degradation of the world's tropical forests and the numbers of threatened species in the world.

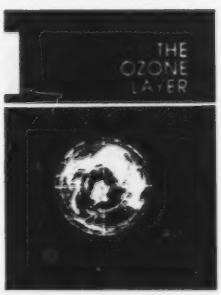
As is proper, the results of these assessments have been regularly published as technical documents. Until now, however, they have not been published in a form that can be easily understood by those without technical qualifications in the subjects concerned. The aim of the UNEP/GEMS Environment Library is to rectify this omission.

This is the second volume in the series, and over the coming months and years we plan to publish many more. Only in this way can the results of UNEP's environmental assessments become widely known. And only if they are widely known is public opinion likely to become sufficiently vociferous to demand that everything possible be done to halt the deterioration of our environment, and preserve for future generations the possibility to survive and flourish as we have been able to do.

Michael D. Gwynne, Director
Global Environment Monitoring System

Contents

Foreword		1
Overview		4
The scientific background	The ozone balance	11
	The threat from pollution	14
	Modelling the atmosphere	17
	What the models tell us	18
	Measuring ozone concentrations	23
	A global warming?	25
Effects on society	Effects of increased ultraviolet radiation	27
	Effects of a changing climate	30
Implications for policy		33
Sources		36



Cover picture shows a map of levels of ozone above the Antarctic prepared by a TOMS satellite. Since 1957, ozone levels during the Antarctic spring have fallen by some 40 percent—see page 23

Foreword

Mostafa K. Tolba

Some 25 kilometres above the Earth's surface lies a delicate veil that protects the inhabitants of this planet from the direct gaze of the Sun. This veil, thinner than gauze itself and just as delicate, is the ozone layer.

Life on Earth depends as much on the presence of this ozone as it does on the presence of oxygen and water. Without it, lethal levels of ultraviolet radiation would reach the Earth's surface, extinguishing life on the green planet just as surely as if the atmosphere were removed altogether.

Since the early 1970s, it has been realized that man has it within his power greatly to reduce the effectiveness of this ozone filter. At this very moment, chemicals released by our industries are eating away at the ozone layer. These chemicals will carry on with their destructive work for probably another century, so long-lived is their presence in the atmosphere.

We can do nothing about the chemicals already in the atmosphere. But we can do something about the chemicals we may put there in the future. We have a commitment to coming generations to leave them with an environment in which they can flourish just as we have. Yet the signs are that—without urgent action—we will bequeath future generations an altered climate and higher levels of ultraviolet radiation.

As yet, there has been little or no damage to the ozone layer. For once the inhabitants of this planet have it within their grasp to arrest a process of environmental deterioration before its effects begin to be felt. If they are to do so, however, they need to have the facts at their finger-tips and the issues clearly and carefully spelled out.

This publication, I believe, does just that. I commend it to anyone who wants to know precisely where we stand on this issue of vital environmental importance.

Mostafa K. Tolba
Executive Director
United Nations Environment Programme

Overview

Ozone is a minor constituent of the Earth's atmosphere, found in varying concentrations between sea level and a height of some 60 km. Its importance to human society is two fold.

ozone prevents the most dangerous ultraviolet wavelengths from reaching the Earth's surface

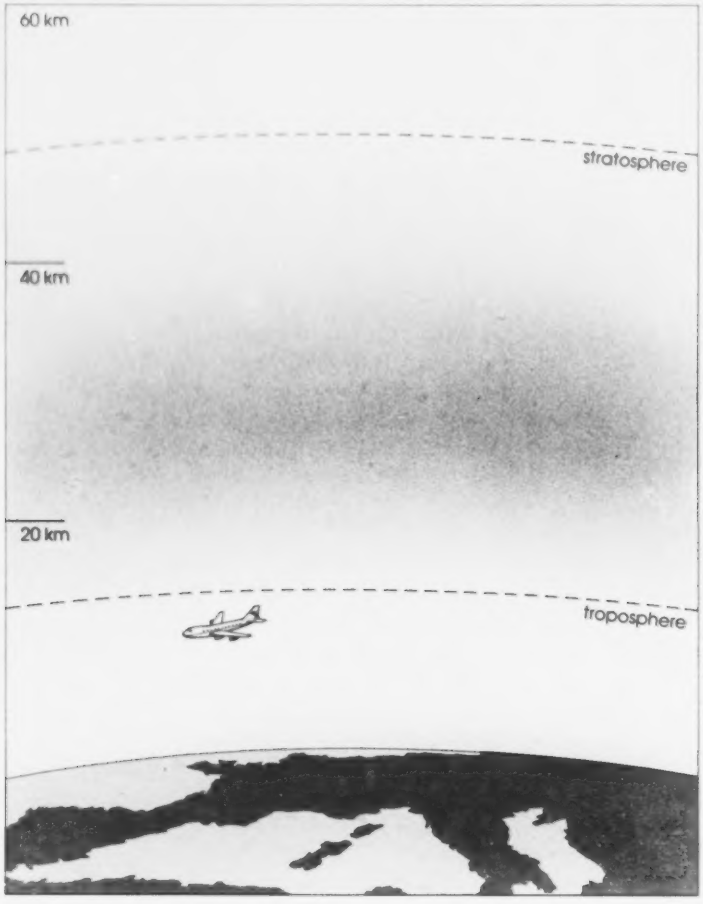
First, ozone acts as a filter for ultraviolet radiation emitted by the Sun. Its presence prevents the most dangerous ultraviolet wavelengths from reaching the Earth's surface at all. It also filters out between about 70 and 90 percent of the less damaging portions of the ultraviolet. Radiation at these wavelengths is responsible for sunburn, snow blindness, eye damage, skin cancer, and the ageing and wrinkling of skin.

Secondly, ozone plays a number of important roles in regulating the Earth's temperature. Like carbon dioxide, ozone is a greenhouse gas. If its concentration in the lower atmosphere were to increase, more of the Earth's infrared radiation would be absorbed before it was lost in space, leading to a warming of the Earth. Higher up in the atmosphere, the process by which ozone absorbs ultraviolet radiation also helps regulate the Earth's temperature. Changes in ozone concentrations at any height can therefore influence the Earth's climate.

Ozone levels in the atmosphere are affected by a number of chemicals that accelerate the speed at which ozone is broken down chemically. The most important of these are simple but highly reactive chemicals containing the elements carbon, hydrogen, chlorine and nitrogen. Most of these are produced, high up in the atmosphere, when normally stable gases—often present in the atmosphere in only minute amounts—are broken down by ultraviolet radiation. These 'trace gases' include the nitrogen oxides, water vapour, chloroform, methane and chemicals known as chlorofluorocarbons (CFCs) used commercially mainly in aerosols, as foam blowing agents and in refrigeration.

there has been a major annual reduction in ozone levels over the Antarctic during the spring

The concentration of these trace gases in the atmosphere is increasing, mainly as a result of industrial activity. Consequently, the ozone layer is under potential threat, particularly from rising levels of the CFCs. The severity of the threat is difficult to estimate for a number of reasons. One is that both the chemistry and the physics of what occurs in the atmosphere is extremely complicated. Another is that the cause of the increasing concentrations of some of the trace gases in the atmosphere is not fully understood; it is therefore difficult to predict how these levels are likely to change in the



future. A third is that the CFCs take some time to travel from the Earth's surface to the heights at which they do their damage; their effects are therefore delayed but—once started—continue for a century or so.

Measurements of ozone levels over the past few decades show that there has as yet been no significant change in the total amount of ozone averaged over the whole globe. However, there are indications of small changes at particular heights, with ozone levels increasing at low levels and decreasing higher up. And for some years now, there has been a major annual reduction in ozone levels over the Antarctic during the spring. The significance of this finding is not yet understood.

These results are relatively new, and represent an important milestone in our knowledge of what is happening in the ozone layer. Until now, possible damage to the ozone layer has been a matter of theoretical speculation. If the new results are confirmed, they represent the first observational evidence of more than a decade's theoretical work.

The new observations are broadly consistent with the predictions about what should be happening to the ozone layer

the CFCs take some time to travel from the Earth's surface to the heights at which they do their damage; their effects are therefore delayed but — once started — continue for a century or so

made by mathematical models of the atmosphere. These models also suggest that, if CFC production continues to increase and the concentrations of other chemicals continue to rise at their present rates, total ozone levels will fall by a few percent, and upper atmosphere ozone levels by much more, during the first half of the next century.

There is likely to be an increase in eye disease and skin cancer, in both humans and domestic stock, at all latitudes. Plant growth could also be affected

If this happens, human society will be exposed to increased ultraviolet radiation. There is likely to be an increase in eye disease and skin cancer, in both humans and domestic stock, at all latitudes. Plant growth could also be affected, resulting in lower crop and timber yields. There could also be widespread effects on aquatic ecosystems, including edible fish, because marine algae, living at the top of the marine food chain, are particularly sensitive to ultraviolet radiation.

The quantitative relationship between a decrease in ozone concentrations and these effects is not yet well understood. A 10 percent reduction in ozone, for example, is likely to lead to an increase of around 20 percent in the incidence of ultraviolet radiation. Experiments are underway to elucidate the effect this might have on human health, crop production and fisheries.

Perturbations in the ozone layer, in conjunction with changing concentrations of other chemicals, are also likely to lead to a warming of the Earth's surface. The best estimate from theoretical models is currently that the temperature will increase by between 1.5 and 4.5 °C by the year 2030.

A temperature rise of this scale would have major effects on human society. The Earth's average annual temperature has varied by more than 1 °C over the past 10 000 years only rarely. Even during the last Ice Age, the average temperature of the Earth's surface was only about 5 °C lower than it is now.

Thermal expansion of the oceans would lead to a slow but steady rise in sea level

Such a warming of the Earth would probably produce much higher average temperatures in some areas—particularly the higher northern latitudes. Average rainfall would increase but many soils would become drier as a result of increased evaporation. Thermal expansion of the oceans would lead to a slow but steady rise in sea level, possibly followed after a century or so by the melting of parts of the polar ice caps.

The effects on society would be widespread and would probably include damaging crop reductions in marginal food-producing areas. Sea level changes might lead to major migrations because much of the human population lives close to

coastlines. The economic base of many countries, and of international trade, could undergo major transformations.

These considerations make international agreements to protect the ozone layer of paramount importance. A Convention for the Protection of the Ozone Layer was signed by many states in Vienna in 1985 but has yet to come into force. Work is in progress to formulate a Protocol to the Convention that will place limits on future emissions of CFCs by limiting production capacity, by restricting the uses made of these chemicals or by some other means. Meanwhile, many countries and economic groupings have taken individual action to introduce legislation to regulate CFC production and use. Because the CFCs may stay in the atmosphere for 100 years or more, and their effects are therefore long lasting, the need to introduce regulations to protect the ozone layer is urgent.

Because the CFCs may stay in the atmosphere for 100 years or more, and their effects are therefore long lasting, the need to introduce regulations to protect the ozone layer is urgent

The scientific background

Life on Earth is critically dependent on the planet's atmosphere. As far as is known, only on Earth does the atmosphere provide a mix of gases, including water vapour, that allows living things to survive. Oxygen and water, of course, were the two prime requirements for the evolution of animal life. But the existence of life also depends on the presence in the atmosphere of small quantities of other gases that play a critical role in filtering radiation from the Sun and regulating the temperature of the Earth's atmosphere and surface.

One of the most important of these is ozone, a simple molecule composed of three oxygen atoms. Ozone is a minor constituent of the atmosphere, comprising only a few millionths of its total volume. If all the ozone contained in the atmosphere from ground level to a height of some 60 km could be assembled at the Earth's surface, it would comprise a layer of gas only about 3 mm thick, weighing some 3 000 million tonnes.

Despite this, life depends on the presence of ozone. Ozone has the ability to absorb ultraviolet radiation emitted by the Sun up to wavelengths of about 320 nanometres (1 nanometre is a millionth of a millimetre, or 10^{-9} m). Ultraviolet wavelengths of 200-280 nm, known as UV-C, are lethal to man and living things but are more or less totally absorbed by atmospheric ozone.

Between 280 and 320 nm, ozone absorbs most, but not all, the radiation. This portion of the spectrum, known as UV-B, is lethal to many forms of life. Even at the low levels that currently reach the Earth, it causes eye damage and skin cancer in man; increased radiation at these wavelengths would be detrimental to human health and could lead to serious effects on the productivity of plants, including many domestic crops, and on

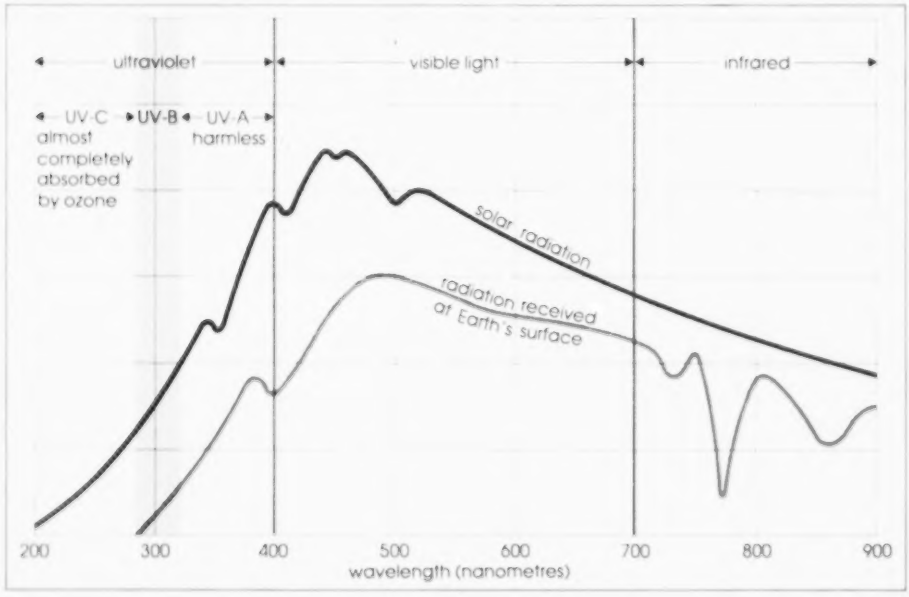


Figure 1 Solar radiation spans wavelengths ranging from about 100 to more than 3000 nanometres (nm) but much of it never reaches the Earth. The 280-320 nm band known as UV-B, which is only partially absorbed by ozone, causes sunburn, eye damage, skin cancer and slows plant growth

marine algae and hence on fish production. Ultraviolet radiation above 320 nm, UV-A, is relatively harmless and little of it is absorbed by ozone.

If ultraviolet radiation were allowed to reach the Earth's surface unfiltered, life—if it existed at all—would have assumed very different forms to those we know today. The fact that most of the Sun's damaging ultraviolet radiation is absorbed in the atmosphere is due mainly to the existence of ozone. Ozone thus acts as a kind of umbrella against the ultraviolet, shielding life on Earth from an extremely harmful form of radiation.

Nearly all the atmosphere's ozone is contained in its lowest two layers: the troposphere, which extends up to about 12 km and contains large amounts of water vapour, often in the form of clouds; and the stratosphere above it, which extends up to about 50 km and is relatively dry and virtually cloudless. Most of the ozone is found between 20 and 50 km above the Earth's surface. The highest ozone concentrations, of around 10 parts per million by volume, occur at a height of 20-25 km (*see Figure 2*). Even here, only about one molecule in every 100 000 is ozone.

Although stratospheric ozone can sometimes descend to the troposphere, the reverse is not true: ozone created in the troposphere never ascends to the stratosphere. Thus if stratospheric ozone is depleted, it cannot be made up with ozone created lower in the atmosphere.

Ozone concentrations at ground level are normally very low. This is just as well because ozone is extremely poisonous; even at very low concentrations, it irritates the respiratory system unpleasantly and dangerously. However, ozone is created during the process that forms photochemical smog. Nitrogen oxides, produced when fossil fuel is burnt, are

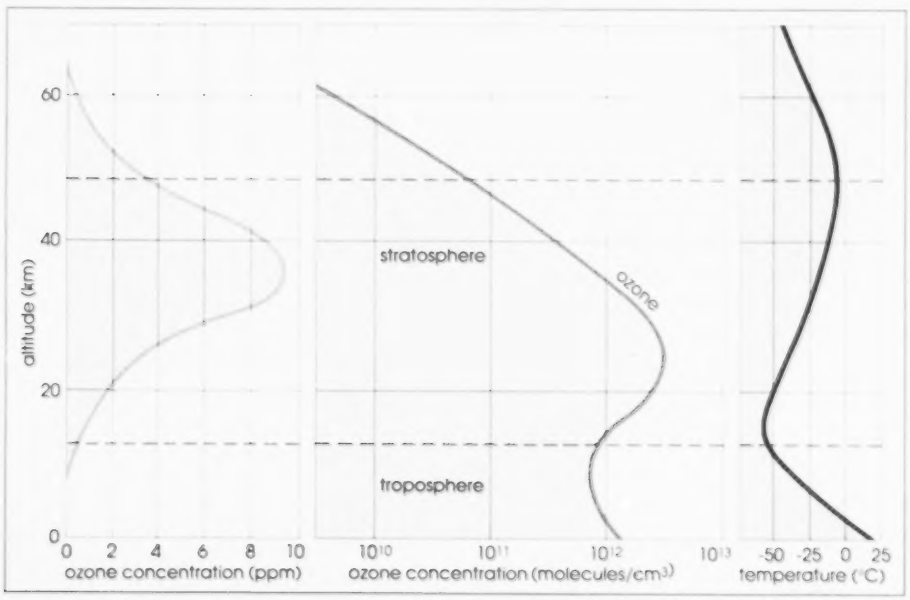


Figure 2 Ozone is found in varying concentrations from the Earth's surface to a height of some 60 km. Its concentration increases sharply in the stratosphere. Maximum ozone concentrations occur at a height of 25-35 km but even here never exceed about 10 parts per million by volume

12

able to catalyse a reaction in the presence of sunlight between molecular and atomic oxygen to produce ozone:

$$O_2 + O \Rightarrow O_3$$

As well as shielding the Earth from harmful radiation, ozone also plays an important role in regulating the temperature of the Earth's surface and atmosphere. The troposphere is heated primarily by radiation from the Earth's surface, but also to some extent from infrared radiation emitted from the stratosphere above. The stratosphere itself is heated by the process in which ozone absorbs ultraviolet radiation. Ozone, therefore, acts as a kind of heat sink for the stratosphere. It follows that if the concentration of ozone in the stratosphere changes, so will the temperature of the stratosphere. Because conditions in the stratosphere eventually affect the troposphere, the latter will also undergo temperature changes, thus affecting the weather and climate at the Earth's surface. These effects depend not only on the total amount of ozone in the atmosphere but also on the way it is dispersed within it.

Two opposing effects are involved. If the concentration of ozone in the stratosphere decreases, less ultraviolet radiation will be absorbed there. More ultraviolet radiation will thus reach the Earth's surface, tending to make the Earth warmer. On the other hand, if less ultraviolet radiation is absorbed in the stratosphere, the stratosphere itself will cool. It will thus emit less infrared radiation, and contribute to a cooling of the Earth.

These effects would approximately cancel one another out if ozone levels were decreased uniformly throughout the stratosphere. However, this would not necessarily be true if ozone levels were decreased more at some heights than at others. The Earth's temperature is particularly dependent on ozone levels in the upper troposphere and lower stratosphere.

In the troposphere, ozone plays a completely different role in helping regulate temperature. Like carbon dioxide, ozone is a 'greenhouse gas'; its presence tends to increase the temperature of the atmosphere and the Earth's surface as a result of the greenhouse effect. This effect arises from the ways in which greenhouse gases absorb or transmit radiation.

Greenhouse gases are relatively transparent to incoming solar radiation, which is absorbed by the Earth's surface and which therefore warms it. As the Earth's surface heats up, it emits more radiation of a longer wavelength which is dissipated into the atmosphere and ultimately into space, thus cooling the Earth. This is the mechanism by which relatively even temperatures are maintained on the Earth's surface. The greenhouse gases, however, interfere with this process because they are relatively opaque to the longer wavelengths emitted from the Earth's surface. By absorbing some of this radiation, they prevent it from being dissipated into space, and thus interfere with the Earth's natural cooling mechanism. As a result, they cause a gradual warming of the Earth's surface and atmosphere.

The ozone balance

The gases in the Earth's atmosphere are normally in a state of dynamic balance. They partake in the global cycles in which elements such as carbon and nitrogen are recycled between plants and animals, the oceans, the soil and the atmosphere. Many of the gases present in the upper atmosphere are broken down by the action of sunlight, releasing highly reactive radicals that react rapidly with one another.

Ozone itself is created in a chain reaction that begins when solar radiation of wavelengths less than 242 nanometres is absorbed by the oxygen molecule which is split into two free oxygen atoms in the process. Each oxygen atom then reacts rapidly with another oxygen molecule to produce ozone. The ozone molecule is broken down when it absorbs UV-B, forming an oxygen molecule and an oxygen atom (*see Figure 3*).

If no other chemicals were present in the atmosphere, these processes would approximately balance one another, resulting in a state of equilibrium in which the average quantity and distribution of ozone in the atmosphere would change little over the years. There would, however, still be substantial variations in ozone levels between the seasons, at different latitudes, and as the intensity of solar radiation varied with both the 27-day and the 11-year solar cycles. The rate at which ozone is created in the stratosphere depends almost entirely on the amount of solar radiation falling on the stratosphere. It cannot be influenced by man.

However, the atmosphere contains small amounts of many different gases that can speed up these chemical reactions, particularly those concerned with the breakdown of ozone. They do so catalytically: they accelerate the rate at which ozone is broken down without themselves undergoing any chemical transformation.

These catalytic gases include the oxides of nitrogen, chlorine and hydrogen. Because the reaction does not affect the catalyst itself, which remains in the same state at the end of the reaction as at the beginning, even very small amounts of these elements—measured in a few parts per billion—can produce major effects on the concentration of ozone in the atmosphere. The catalytic elements, in effect, spend their lives speeding up reactions that break down ozone, each catalytic molecule attacking as many as a thousand molecules of ozone in turn (*see Figure 3*).

Although the molecules involved are very simple, the details of atmospheric chemistry are exceedingly complicated. The driving force of the chemical reactions is ultraviolet radiation, in the form of energetic particles called photons. For this reason, this branch of chemistry is known as photochemistry, and it differs

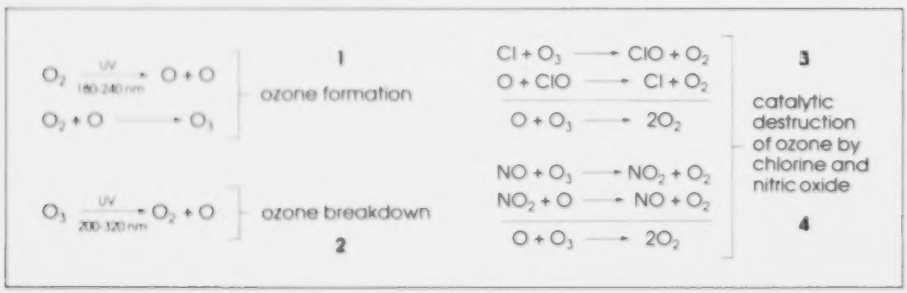

$O_2 \xrightarrow[180\text{-}240\,nm]{UV} O + O$
$O_2 + O \longrightarrow O_3$
1
ozone formation
$O_3 \xrightarrow[200\text{-}320\,nm]{UV} O_2 + O$
ozone breakdown
2
$Cl + O_3 \longrightarrow ClO + O_2$
$O + ClO \longrightarrow Cl + O_2$
$O + O_3 \longrightarrow 2O_2$
3
$NO + O_3 \longrightarrow NO_2 + O_2$
$NO_2 + O \longrightarrow NO + O_2$
$O + O_3 \longrightarrow 2O_2$
4
catalytic destruction of ozone by chlorine and nitric oxide

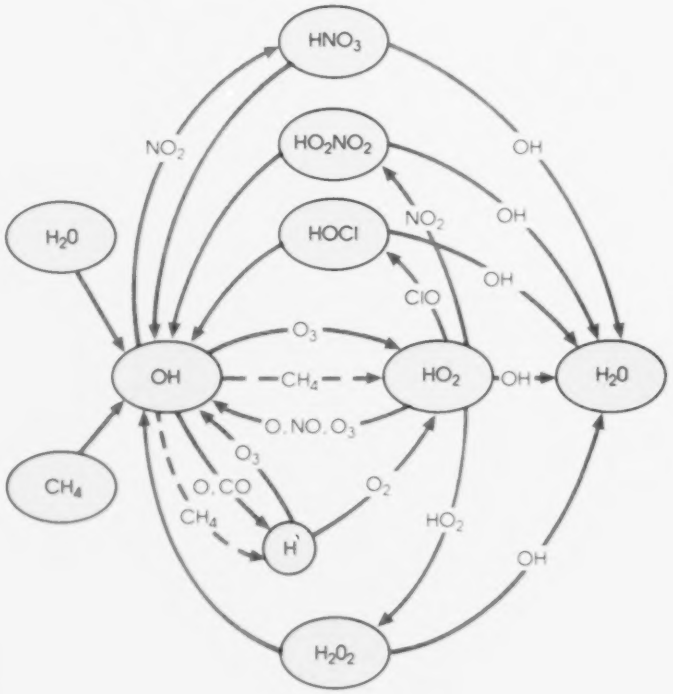
Figure 3 Formation (1) and breakdown (2) of ozone occur naturally in the stratosphere but the rate of ozone breakdown can be greatly accelerated by catalysts such as chlorine (3) and nitric oxide (4)

Atmospheric photochemistry

The dynamic balance of the gases in the stratosphere is maintained as a result of a huge number of interlinked chemical reactions. Hydrogen, nitrogen and chlorine are among the most important elements involved in these reactions, and the illustrations on this and the facing page summarize the main reactions in which they are involved.

During the 1970s and early 1980s, there were rapid advances in our understanding of stratospheric photochemistry. More recently, however, although progress has continued, the pace of advance has slackened, suggesting that the overall process is now much better understood than a few years ago.

Numerical models of atmospheric photochemistry have to incorporate all these reactions, and include data on their reaction rates and how these change with both temperature and pressure. Despite the complexities of the system, most chemical models of the atmosphere now produce broadly similar predictions. There is thus growing confidence that attempts to forecast how ozone levels may change as a result of changing concentrations of other chemicals are likely to be essentially correct.



hydrogen cycle

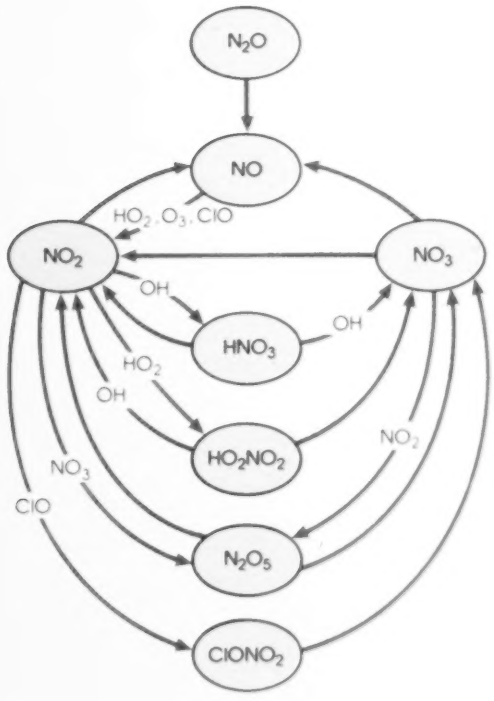
markedly from the kind of chemistry with which we are familiar on the Earth's surface. At the temperatures and pressures prevailing in the stratosphere, photons cause the disintegration of simple molecules that would normally be highly stable.

Many of the products of photochemical reactions are what are called radicals, such as the hydroxyl (OH) and chlorine (Cl) radical, which are highly reactive. They therefore react rapidly with other chemicals in the atmosphere, including oxygen and ozone. The net effect, which determines the dynamic balance of the gases in the atmosphere, depends on the relative speeds of the many hundreds of chemical reactions that occur there. Furthermore, the speeds of these reactions vary greatly with changes in temperature and pressure.

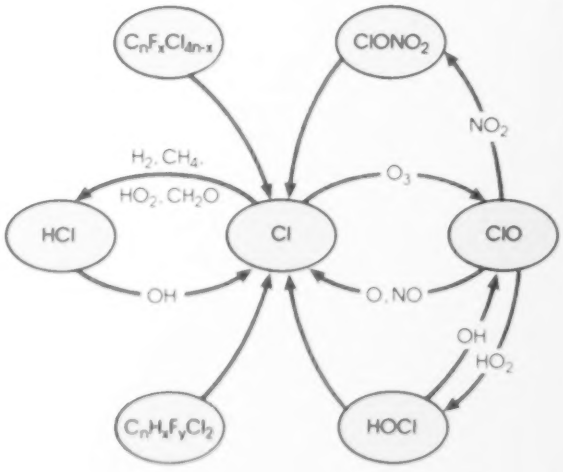
This makes predicting the effects of increased concentrations of these chemicals in the stratosphere very difficult. If it is to be done effectively, account must be taken simultaneously of all the different chemicals that are present.

This situation is further complicated by the fact that the reactions that occur in the troposphere, where there is less ultraviolet radiation and where temperatures and pressures are very different from those in the stratosphere, are often quite different from those that occur higher up. For example, the presence of a simple inorganic molecule may cause an increase in ozone concentration in the troposphere but decrease it in the stratosphere.

A detailed understanding of the workings of atmospheric photochemistry has been achieved only in the past decade or two. In some areas, such as the important reactions in which the hydroxyl radical, OH, is involved, knowledge is



nitrogen cycle



chlorine cycle

even more recent, dating from the late 1970s. Furthermore, there are still many unknowns. The box on this and the facing page summarizes some of the details of atmospheric photochemistry.

What goes on in the atmosphere is, of course, of intrinsic scientific interest. However, the need to understand the photochemistry of the atmosphere has become more urgent recently as the concentrations of a number of chemicals in the atmosphere have begun to rise. Levels of carbon dioxide, produced in quantity as fossil fuels are burnt, have been rising steadily for many decades. But only since about 1960 have the concentrations of other chemicals been increasing, some of them extremely quickly. These chemicals threaten both to alter the balance of the ozone layer and to affect the Earth's temperature.

The threat from chemical pollution

Compounds containing hydrogen, nitrogen, chlorine and fluorine are produced in quantity in industrial society. What happens to them subsequently is of crucial importance to the ozone layer. Many of them combine with one another in the lower atmosphere, producing molecules such as nitric and hydrochloric acids. These are soluble in water and hence are rained out of the atmosphere onto the Earth below. They therefore never reach the stratosphere and do not pose a threat to the ozone layer itself—although they may cause extensive pollution in the form of acid rain.

It is a different story, however, if the catalytic elements enter the atmosphere in the form of stable and relatively insoluble molecules such as nitrous oxide, methyl chloride, methane, carbon tetrachloride, and compounds that contain both chlorine and fluorine and which are known as chlorofluorocarbons (CFCs).

These trace gases linger for long periods in the troposphere, and are eventually transported up into the stratosphere. There they react with other chemicals under the influence of ultraviolet radiation, forming the active radicals containing hydrogen, nitrogen, chlorine, fluorine and bromine that speed up the breakdown of ozone so dramatically.

Table 1 summarizes some of the essential data on the trace gases that most affect ozone concentrations. Carbon dioxide is also included because it affects ozone concentrations through its ability to cool the stratosphere, slowing down the rate at which ozone is broken down by other chemical actions and effectively increasing stratospheric ozone concentrations.

With the exception of the CFCs—and Halon 1301, a fire extinguishing agent that could deplete ozone levels rapidly and whose use is expanding fast—the gases included in Table 1 are produced both naturally and as a result of industrial activity. Methane, for example, is released naturally (as 'swamp gas') from muddy pools and peat bogs, is produced during rumination in cattle and is often a by-product of rice farming as a result of the underwater fermentation of organic matter in paddy fields.

The causes of the increasing concentrations of many of the trace gases listed in Table 1 are therefore extremely complex. Indeed, it is far from clear why

Table 1 **Trace gases affecting ozone concentrations**

gas	formula	average lifetime in atmosphere (years)	average global concentration (ppbv)	annual rate of increase (percent)
CFC 11	$CFCl_3$	75	0.23	5
CFC 12	CF_2Cl_2	110	0.4	5
CFC 113	$C_2F_3Cl_3$	90	0.02	7
Halon 1301	CF_3Br	110	very low	11
nitrous oxide	N_2O	150	304	0.25
carbon monoxide	CO	0.4	variable	0-2
carbon dioxide	CO_2	7	344,000	0.4
methane	CH_4	11	1,650	1

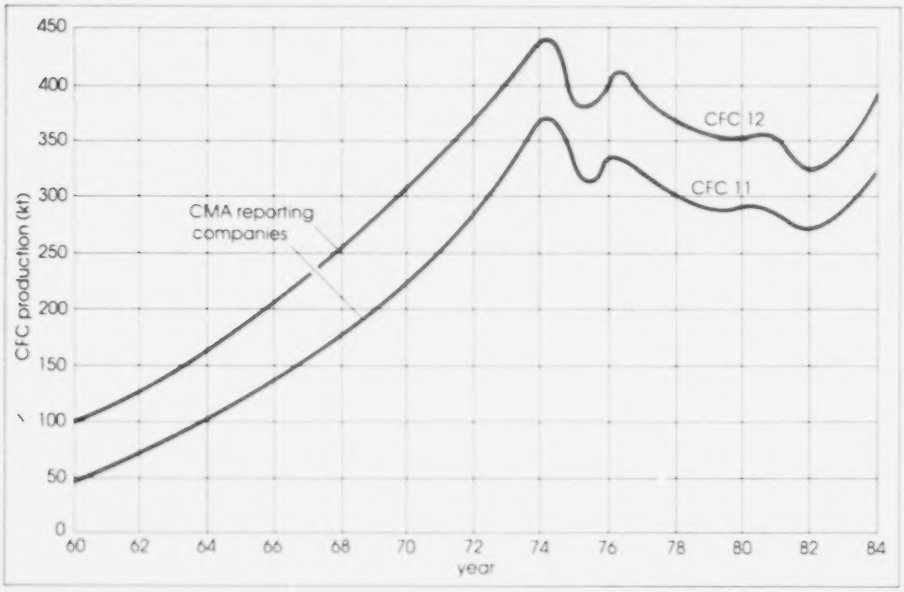


Figure 4 Production of CFCs 11 and 12 has increased substantially since 1960. After a slow-down in the mid-1970s, production appears to be increasing again. Graphs are compiled from statistics supplied by the Chemical Manufacturers' Association (CMA)

the atmospheric concentrations of methane and carbon monoxide, for example, are increasing at all. This makes it difficult to predict future levels of these gases in the atmosphere, and their likely effects on ozone levels. Furthermore, the gases listed in Table 1 are not the only ones capable of influencing ozone levels. Many other gases, including some of the less widely used CFCs, can do so. Relatively little is known about the concentrations and rates of increase of most of these gases but it is estimated that their combined potential effect on ozone destruction amounts to about 25 percent of that of CFC 11 and 12.

Since the early 1960s, scientists have been worried that, as more and more chemicals were released into the atmosphere, ozone concentrations in the stratosphere would be significantly reduced, allowing more harmful UV-B radiation to reach the Earth's surface. Aircraft, for example, produce large quantities of water vapour and nitrogen oxides in their exhausts. Although most subsonic aircraft fly well below the stratosphere, supersonic aircraft fly much higher, in the lower stratosphere.

In the mid-1960s, it was predicted that by the mid-1980s there would be more than 500 supersonic airliners in operation, and that these might produce sufficient stratospheric contaminants to reduce ozone levels substantially. In the event, this turned out to be a false alarm, for there are still only a score or so supersonic airliners in operation. However, several countries run fleets of high-altitude supersonic military aircraft, and these could eventually have an effect on ozone concentrations. To date, there is no evidence that aircraft flights of any kind have actually produced detectable changes in ozone concentrations, although recent theoretical studies now suggest that subsonic aircraft flights should eventually lead to a small increase in ozone in the upper troposphere and the lower stratosphere.

There is also concern that increased production of nitrogenous fertilizers must eventually lead to the release of more nitrogen compounds into the atmosphere, some of them in the potentially harmful form of nitrous oxide. In fact, levels of nitrous oxide in the atmosphere are increasing at about 0.25 percent a year, and their effects are likely to be long lived. The average nitrous oxide molecule, once released into the atmosphere, stays there for about 150 years.

Another group of chemicals that also has a long residence time in the atmosphere is the chlorofluorocarbons, also known as freons. These gases are used as the propellants in aerosols, in refrigeration technology, as solvents and as foam-producing agents. The two most commonly used are CFC 11 and 12. The

residence time in the atmosphere of CFC 11 is estimated at 75 years and that of CFC 12 at 110 years. Thus even if the rate of release of these gases into the atmosphere were eliminated or sharply reduced now, it would take many decades for the atmosphere to return to its original composition.

CFCs do not occur naturally and are produced only industrially. In the long term, virtually all manufactured CFCs end up in the atmosphere. Furthermore, they are not destroyed in the troposphere but, over a period of a few years, diffuse up into the stratosphere. There they are slowly broken down as a result of the action of sunlight, producing the free chlorine atoms that play such an active part in ozone destruction.

The known production of CFCs increased rapidly up till the mid-1970s, when it reached a peak. It then began to decline as awareness grew of the potential dangers of using CFCs as aerosol propellants. More recently, production has started to increase again and 1984 levels equalled those of 1977 (*see Figure 4*), largely because CFCs are being used increasingly in non-aerosol applications—CFC 11 as a foam-blowing agent and CFC 12 as a refrigerant. Levels of CFCs in the atmosphere have also been steadily increasing (*see Figure 5*).

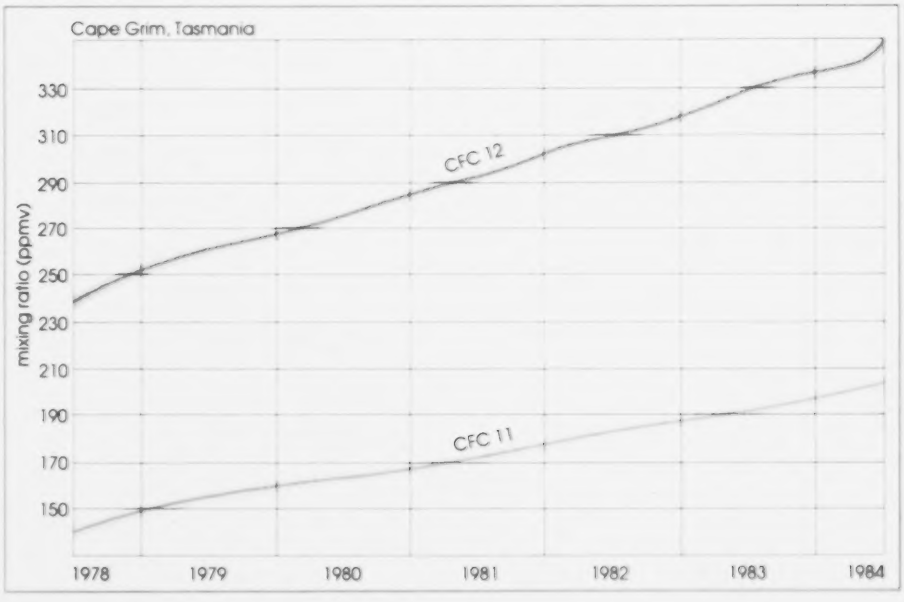


Figure 5 Monthly measurements of CFC concentrations in the atmosphere since 1978 show a slow but steady rise. Because CFCs remain in the atmosphere for as long as 100 years, it would be a long time before decreases in CFC production caused atmospheric concentrations to fall

Modelling the atmosphere

Each of the chemicals mentioned in the previous section has a different effect on levels of ozone in the atmosphere, and the effects are different at different heights. From a knowledge of the speed of different chemical reactions, scientists are able to make mathematical models that predict the effects of changing concentrations of the trace gases on ozone levels at different heights.

Many major problems surround the construction of these models. Until recently, for example, there were two main types of model: one type made detailed assumptions about the chemical kinetics of what went on in the atmosphere but tended to ignore other important factors such as the general circulation of the atmosphere; the other included great detail about atmospheric circulation but little chemical detail. This gap is now being closed but the final objective—a model of the atmosphere that includes all that is known of both chemistry and atmospheric dynamics—is still well beyond the reach of contemporary science.

Atmospheric models also vary greatly in their complexity. The simplest—the zero-dimensional models—study only what occurs at a single point in the atmosphere. These models are useful, for example, for studying the effects of changes in reaction rates on the chemical system.

One-dimensional models are used to study what happens in a vertical column of the atmosphere. They are useful for studying vertical movement in the atmosphere, or global effects on ozone levels averaged over the year. Until a few years ago, this type of model was the one most used to evaluate changes in the ozone layer.

Two-dimensional models include variations with latitude, and hence are often used to investigate the very complex horizontal components of atmospheric circulation. Some of them now include quite complex chemical dynamics, and can be used to investigate the chemical changes that occur with the seasons and at different latitudes. Others are used to examine the effects of changing ozone levels on temperatures throughout the atmosphere.

Three-dimensional models are the most sophisticated, modelling two horizontal dimensions as well as the vertical one. These general circulation models are widely used to study climate changes, and include rough approximations of what is known about atmospheric circulation and the complex interactions that occur between the atmosphere and the oceans. To date, however, they have been run for only short periods of time, and most of them include only rudimentary data on chemical kinetics. While they provide a broad picture of what might happen to the Earth as a whole as conditions change, they are not yet sufficiently reliable to predict detailed changes at a regional or national level.

What the models tell us

These models can be used to predict what changes might be produced in the total amount of ozone in the atmosphere, and in the way in which it will be redistributed with height, as a result of increases in the concentration of the trace gases. Many different models are now in operation, and each is being continually refined as knowledge of what goes on in the atmosphere improves.

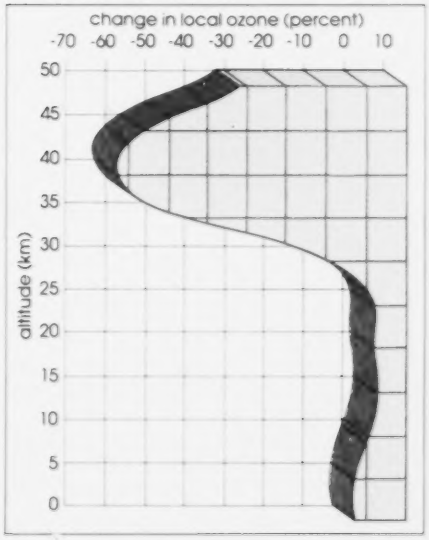
While few of these models provide identical results for a standard set of assumptions, their results are now nearly all in broad agreement. They all predict the same general trends, though some predict somewhat sharper changes than others. The results of the model runs that are described below are therefore typical of the range of models used.

The simplest way to study effects on the ozone layer is to use a model in which just one variable is changed at a time—for example, an increase in CFC release to the atmosphere. Studies of this type provide a good illustration of the effects of different trace gases on the ozone layer.

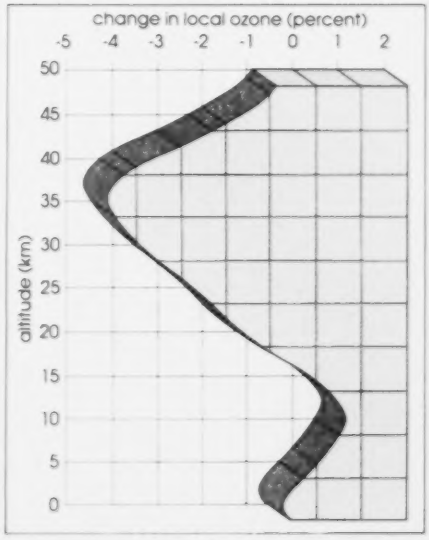
In most cases, the continuous release of a chemical into the atmosphere eventually results in a new atmospheric equilibrium. The atmosphere behaves in a similar way to a tank with a hole in the bottom being filled by a tap. The water level in the tank begins to rise, and eventually the water pressure above the hole becomes sufficient to force just enough water out to compensate for the water coming in from the tap. The water level then stays constant, and a 'steady state' is reached.

The analogy with ozone depletion needs spelling out in more detail. The 'tap' is the equivalent of ozone production through the action of sunlight. As already mentioned, this cannot be altered by man; the ozone tap is therefore fixed at a

6 CFCs 11 and 12 produced at 1980 rate
total ozone: -7 percent



7 nitrous oxide increased by 20 percent
total ozone: -2 percent



Figures 6-9 show predictions made by mathematical models of the effect of increasing the concentration of different chemicals in the atmosphere. Increases in the concentrations of the CFCs (6) and nitrous oxide (7) both decrease total ozone by a few percent overall but cause substantial reductions at heights of about 40 km

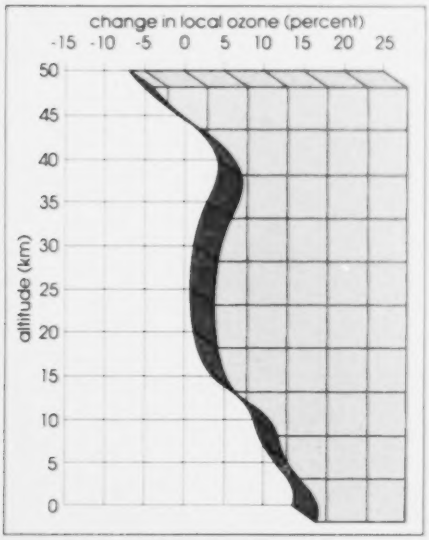
more or less constant level. What is changing is the size of the hole in the bottom of the tank. Increasing levels of trace gases tend to make the hole bigger, with the result that the level in the tank—the ozone level—tends to fall until a new point of equilibrium is established. The figures that follow relate to this steady state condition.

For example, the models show that increasing levels of CFCs and nitrous oxide both decrease the total amount of ozone in such a 'steady state' atmosphere. More specifically, they suggest that if CFC 11 and 12 continue to be produced at the rate at which they were in 1980—and the concentration of all other chemicals is held constant—the end result would be a lowering of total ozone by some 7 percent; levels would change little up to heights of about 25 km but would then drop dramatically, by as much as 60 percent at a height of 40 km (*see Figure 6*). If nitrous oxide levels were increased by 20 percent, the effects on ozone concentrations would be broadly similar though the overall reduction would be much less—only about 2 percent (*see Figure 7*).

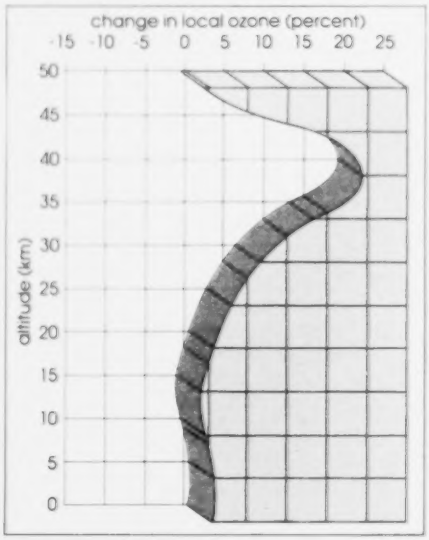
Other chemicals produce quite different results. If the concentration of methane were doubled, for example, total ozone levels would actually increase, by about 3 percent (*see Figure 8*). This is because methane reacts with the chlorine radical, Cl, thus reducing its concentration in the atmosphere. Fewer free chlorine radicals are then available to catalyse the breakdown of ozone.

Doubling the concentration of carbon dioxide would also increase total ozone (*see Figure 9*) by about 3 percent, though for a different reason. Carbon dioxide is a greenhouse gas, and increasing concentrations of it in the troposphere result in increased temperatures. However, in the stratosphere temperature

8 methane concentration doubled
total ozone: +3 percent



9 carbon dioxide doubled
total ozone: +3 percent



Increasing methane levels (8) would increase total ozone because methane reacts with the catalyst chlorine. Higher levels of carbon dioxide (9) would also increase total ozone but for a different reason: more carbon dioxide would produce major temperature changes in the atmosphere

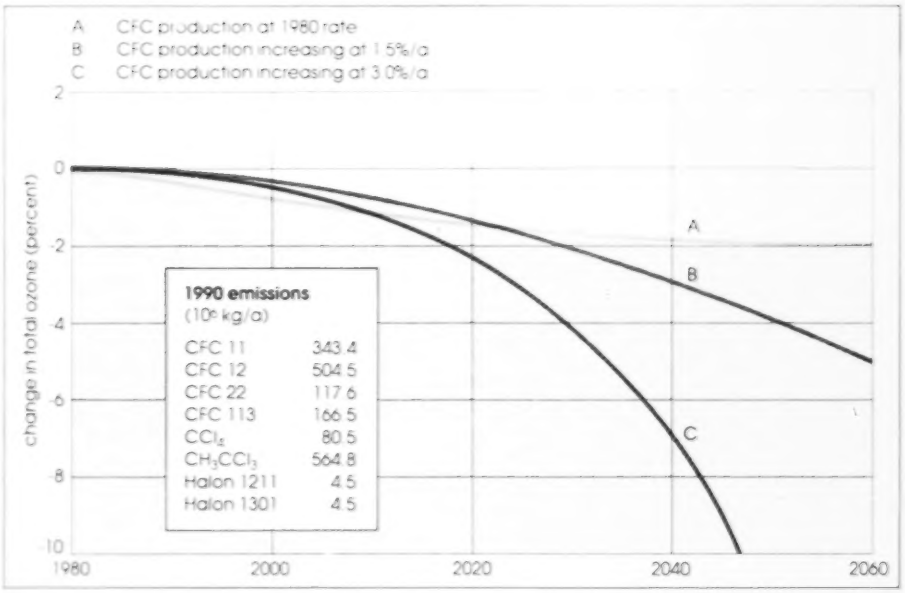


Figure 10 shows the effects of different levels of emissions of all the major ozone depleting substances on total ozone levels. These predictions all assume that other chemicals continue to increase at their current rates. An increase of 3 percent a year in the chemicals listed on the figure would lead to a rapid decrease in ozone levels, with damaging levels of UV-B reaching the Earth's surface during the first half of the next century

will decrease because carbon dioxide is the main infrared radiator that cools the stratosphere. Because chemical reaction rates depend critically on temperature, some more so than others, the overall effect of more carbon dioxide is to increase ozone levels as a result of decreased stratospheric temperatures.

In the real world, the concentrations of many different chemicals in the atmosphere are likely to change simultaneously. Consequently, realistic models of what would happen to ozone levels have to take account of the effect not only of each chemical but of their reactions with one another as well. This has led scientists to construct what are called 'multiple perturbation' models of the atmosphere which try to account for as much of the complex chemistry that occurs in the troposphere and stratosphere as is possible.

An important feature of these models is whether or not they include what is known as 'temperature feedback'. Because most trace gases are also greenhouse gases, increases in their concentrations tend to alter the temperatures of the troposphere and stratosphere. This, in turn, alters reaction rates. Models which take account of this temperature feedback mechanism tend to produce markedly different results from those that do not. The model results included in this publication are from models that incorporate temperature feedback.

One of the problems in modelling the atmosphere is that the cause of the increases in concentrations of some of the trace gases is not fully understood. It is therefore difficult to predict how their concentrations are likely to change in the future. Some simplifying assumptions have to be made. When atmospheric models are used to assess effects on ozone levels, it is often simply assumed

that the concentrations of methane and nitrous oxide will continue to build up in the future at the same rate as they have in the recent past. A similar but slightly more sophisticated assumption is made for carbon dioxide. The US Department of Energy has produced a scenario for the future of carbon dioxide production in which atmospheric levels increase initially by about 0.5 percent a year. This figure increases gradually over the years.

For the CFCs, somewhat more precise assumptions are often made. Three representative ones are that CFC production stays constant at 1980 levels, or that it increases at 1.5 or 3.0 percent a year (thus doubling every 47 and 24 years respectively). In very broad terms, the first of these assumptions is equivalent to international action being taken to ban further increases in CFC production; and the second and third are equivalent to there being limited or no international action to control CFC production. It is also possible, of course, that the industry might take voluntary action to limit production or restrict the uses to which its products are put.

Figure 10 shows just how critical such actions might be. If CFC production is held constant at projected 1990 levels, the multiple perturbation model shows that there would be only small depletions in total ozone levels in the future. This is largely because the effect of the CFCs would be offset by the increased concentration of methane. If CFC production increases at 1.5 percent a year, average global ozone levels would fall by about 3 percent in 60 years time. But if CFC production increases at 3 percent a year, ozone levels would be reduced by more than 10 percent in 60 years time. The effect would get worse with time, and would be even more pronounced if methane levels did not continue to increase at their present rates.

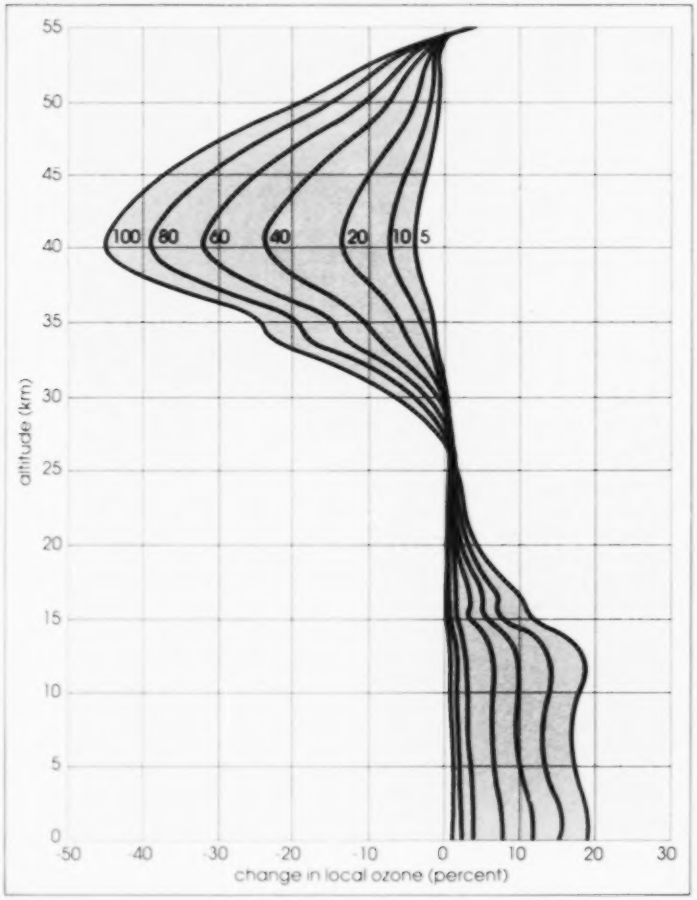


Figure 11 shows predictions of ozone levels with height as a result of increasing CFC production by 1.5 percent a year, after periods of 5 to 100 years. Though the overall reduction is modest, at a height of 40 km reductions would reach more than 40 percent within a century

24

Figure 10 shows only the effect on total ozone levels. What would happen in practice is that there would be increases in ozone levels near the Earth's surface, and large decreases at higher altitudes, with a maximum effect at about 40 km (*see Figure 11*).

These effects would also be much greater nearer the poles than over the equator, and much greater in spring than at other seasons. The latitudinal effect would be the most pronounced. For example, in a scenario in which CFC production is held at 1980 rates, nitrous oxide and methane increase at current rates, and carbon dioxide levels remain constant, total ozone depletion in a northern spring would reach 11 percent at 80 °N by the year 2030; at the equator, it would be only a little more than 1 percent. For comparison, the same scenario produces a global average ozone depletion of 2 percent by the year 2030.

Similar models can also be used to show the effect of the long lifetime of the CFCs in the atmosphere. For example, if all CFC production were halted in the year 2000, ozone concentrations would continue to fall for a further 5 to 10 years, after which they would slowly begin to recover again. Even so, it would be many decades before they returned to near their original levels.

The message from the models made so far is clear. The fate of the ozone layer hangs critically on how the concentrations of a number of chemicals in the atmosphere change with time. The main threat comes from the CFCs, and its magnitude is reduced only as a result of the increasing concentration of methane and to a lesser extent carbon dioxide. Because no one understands why methane concentrations are increasing so rapidly, ozone predictions are hazardous. But if methane levels were to stop rising or fall, and CFC production continued unabated, the ozone layer would be in serious danger.

Mathematical models, of course, are not the only way of finding out what is going on in the atmosphere. The other course of action is to measure chemical concentrations, and analyse how they are changing over time. Monitoring atmospheric change in this way provides a good check on the accuracy of mathematical models. How well do measurements agree with what the models predict?

Meaasuring ozone concentrations

One major problem surrounds the comparison of ozone measurements and model predictions. Most of the predictions suggest that any effects already produced by the trace gases would be very small. Yet ozone levels can vary naturally by as much as 6 percent in any year. It is thus extremely difficult to detect the 'signal' of a small long-term trend against the much larger background 'noise' created by monthly—and geographical—variations.

The total amount of ozone in the atmosphere has been measured from many different sites for many years, using a variety of different techniques. Of these, measurements made with an instrument known as the Dobson spectrophotometer are among the most useful. A statistical analysis of these data from all over the world reveals that the total ozone concentration, averaged over the whole globe, neither increased nor decreased over the period 1970-84.

There is, however, some observational evidence that the distribution of ozone in the atmosphere may be changing at other latitudes. Measurements from stations that monitor ozone levels from balloons indicate that ozone concentrations may be increasing slightly in the troposphere and decreasing slightly in the stratosphere. Models predict that there should be an effect of roughly this size. Unfortunately, the network of balloon measurements is still too small for these measurements to be taken as concrete proof of a global change in ozone distribution, or as confirmation of the validity of the models.

Another set of observations has been produced using different measuring techniques. These show that ozone concentrations have apparently decreased by some 2-3 percent over the decade 1970-80 at heights of 30-40 km.

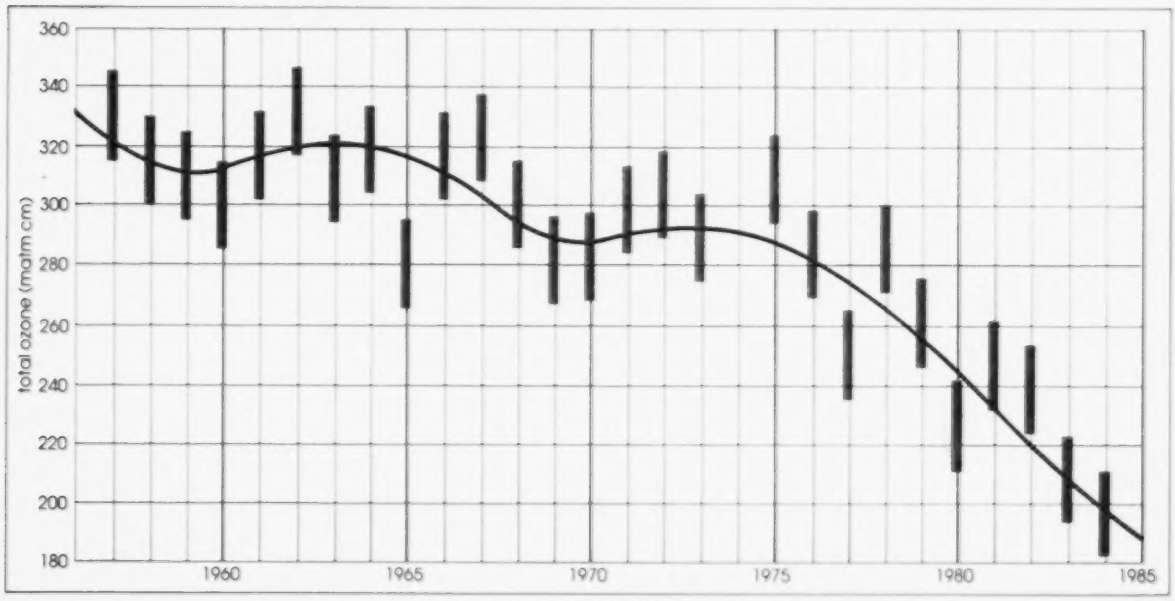
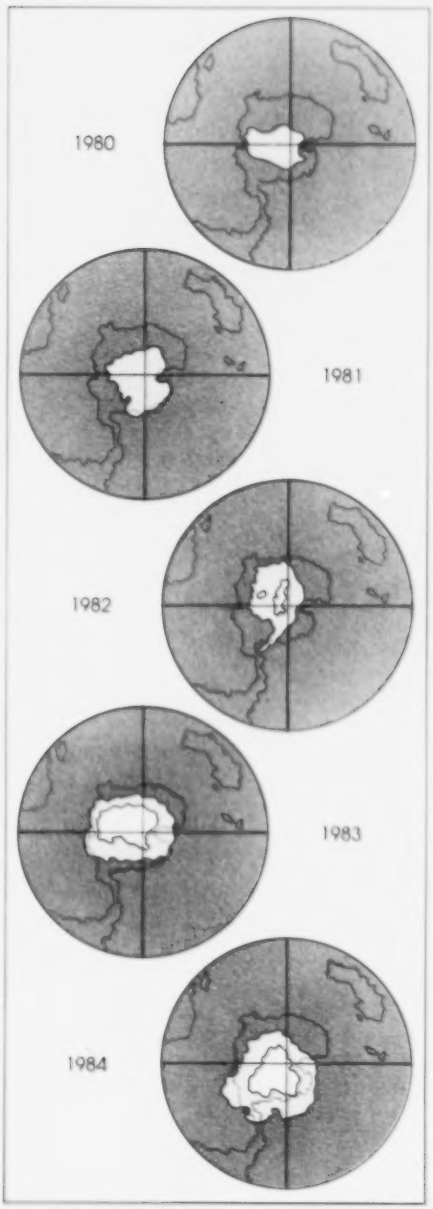


Figure 12 Measurements made at Halley Bay in the Antarctic show that ozone levels have fallen during the Antarctic spring by some 40 percent since 1957. The effect appears to be accelerating but the causes of the decrease have still be explained

Figure 13 shows simplified maps of Antarctic ozone levels prepared by a TOMS satellite on 7 October between 1980 and 1984. Maps show how much the low level ozone regions have grown in just five years



Again, computer models of the behaviour of the atmosphere predict broadly similar results.

While controversy still surrounds these results, this is not true of the most surprising discovery of the past few years. A spectrometer at Halley Bay in the Antarctic has been used by the British Antarctic Survey to measure ozone levels almost above the South Pole every October since 1957. These measurements show that the total amount of ozone above the Antarctic has decreased by nearly 40 percent since 1957, with most of the decrease occurring since the mid-1970s (*see Figure 12*). Since 1979, these measurements have been confirmed by observations from satellites. Much more recently, satellite observations have shown that this damage to the ozone layer above the Antarctic may extend as far towards the equator as 45 °S—though the effect is far less pronounced than it is at the Antarctic.

Scientists have yet to produce any accepted explanation of these findings, which are not predicted in the computer models. Clearly, there is a hole in the ozone layer above the South Pole, and the depth of this hole appears to be increasing. It occurs only during the Antarctic spring. Although this could herald the beginning of general ozone decreases at all latitudes, it might equally result from the special geophysical conditions that exist near the Earth's poles, particularly the southern one. Models of the atmosphere do predict, as we have seen, that if total ozone levels are depleted over the next century, the effect is likely to be several times more severe over the poles than over the equator.

A global warming?

Because ozone is a greenhouse gas, changes in tropospheric ozone levels will affect the temperature of the Earth's surface and atmosphere. Further effects will be caused in the stratosphere where ozone acts as a heat sink, absorbing incoming solar radiation.

While the effects of ozone alone could be calculated relatively simply, there is little point in doing so without considering the effects of the other trace gases. It is these gases that are likely to affect ozone levels, and these gases are also, in their own right, greenhouses gases themselves. In fact, although carbon dioxide is usually thought of as the greenhouse gas *par excellence*, other trace gases—on a molecule for molecule basis—are likely to produce more major effects. It has been calculated, for example, that one molecule of CFC 11 or 12 is likely to have a similar effect on climate as 10 000

Once again, to predict the overall effect on global temperatures means estimating future concentrations of the various trace gases in the atmosphere. Using similar assumptions to those used in the multiple perturbation models, it turns out that the expected temperature rise due to increasing levels of carbon dioxide is about equal to the temperature rise produced by all the other trace gases combined. By the year 2030, carbon dioxide would produce a global warming of about 1.5 °C and the other gases a further rise of 1.5 °C, making a total rise of some 3 °C (*see Figure 14*).

The model used to calculate these results assumes that the temperature rise would occur without any lag caused by the time needed to warm up the Earth. In practice, there would be a considerable delay, perhaps of tens of years, because of the long time required to heat up the enormous mass of the world's oceans.

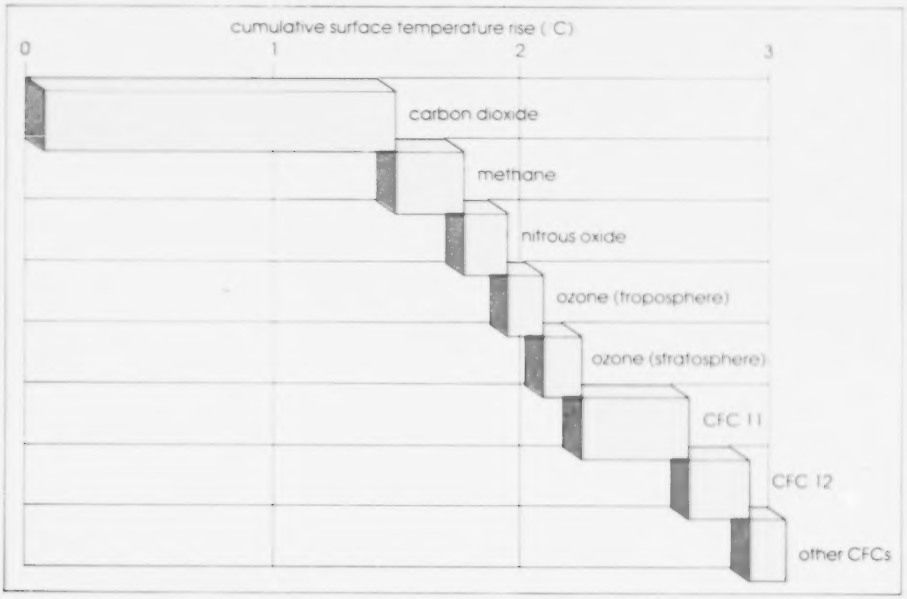


Figure 14 Predicted temperature rises caused by increasing concentrations of carbon dioxide and the other greenhouse gases by the year 2030. The predicted rise is about 3 °C, of which only about one-half would be caused by carbon dioxide itself

28

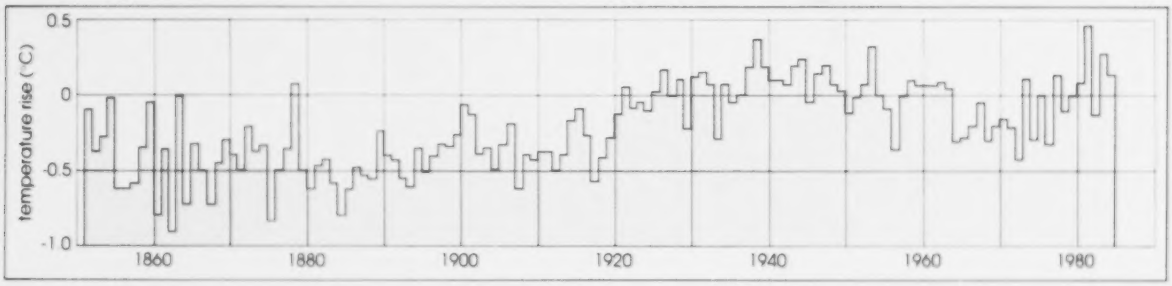


Figure 15 Average annual temperatures of land masses in the northern hemisphere since 1850. Three phases can be distinguished: a slow rise to 1940; a sharp fall to about 1970; and a rapid rise to the present day. The overall rise—of some 0.5 °C—is thought to be at least partially due to greenhouse warming

Scientists estimate that perhaps half of the 3 °C rise would actually occur by the year 2030, with the other half taking a few decades longer to materialize.

Many uncertainties are involved in making such predictions. The models used cannot accurately take into account all the complex variables involved, and estimates of the models' accuracy suggests that the result should really be quoted as a temperature rise of 3 °C, plus or minus 1.5 °C. Even this assumes that future levels of the trace gases can be accurately predicted. Relatively small changes in these levels could alter the end result substantially. What is sure, however, is that if levels of the greenhouse gases continue to grow in the future at the speed at which they are currently growing, the Earth will get warmer.

Indeed, there is increasing evidence that this is already happening. A record of the temperatures of land masses in the Northern hemisphere since 1850 now appears to show that the Earth is already warming up. Although the total variation in temperature over the past 130 years or so is less than 1.5 °C, there appears to have been a rise in temperature over this period of about 0.5 °C. This comprises a slow rise in temperature during 1885-1940, a sharper fall to about 1970, followed by a rapid rise from then on (*see Figure 15*). Exactly what has caused these changes is difficult to determine. Most scientists currently believe that the short-term changes result from such things as volcanic eruptions and changes in solar intensity, but that the long-term trend involves greenhouse warming.

It is thought that the situation since 1960 is very different from the one that preceeded it. Since 1960, gases other than carbon dioxide have been increasing the greenhouse effect. Models of the climate suggest that, in theory, there should have been a temperature rise of 0.6 to 2.0 °C since 1960. However, because of the 'thermal lag' caused by the time the oceans take to warm up, we may actually have experienced only about half of the warming generated by increasing concentrations of the greenhouse gases. What is observed in practice, therefore, ties in fairly well with what current models of the atmosphere predict. Whether this is just coincidence or is confirmation of the validity of the models remains unclear.

A temperature rise of some 3 °C by the year 2030, though it may sound small, could have dramatic effects on life on Earth. For comparison, the average temperature of the Earth was only 5 °C less during the last Ice Age than it is now. Furthermore, during the past 10 000 years, the Earth's average temperature has probably varied by more than 1 °C on only very rare occasions. The possible effects on society of such a temperature rise are examined in more detail at the end of the next section.

Effects on society

Changes in future ozone levels could produce two quite different effects on society. Firstly, a decrease in stratospheric ozone levels could lead to increased ultraviolet radiation at the Earth's surface. Secondly, changes in the ozone distribution—for example, an increase in tropospheric ozone and a decrease in stratospheric ozone—could affect the Earth's average temperature.

Effects of increased ultraviolet radiation

The portion of the Sun's ultraviolet radiation that is partially absorbed by ozone lies between wavelengths of 290 and 320 nanometres. Known as the UV-B, this portion the spectrum causes sunburn, snow blindness, eye damage, skin cancer, and the ageing and wrinkling of skin. In this region, the shorter wavelengths have much more effect on biological tissue than the longer ones. However, because the atmosphere filters shorter wavelengths more effectively than longer ones, the middle region of the UV-B—with wavelengths of about 305 nm—has the highest biological action.

At the equator, under clear skies, about 30 percent of this middle region of the UV-B is transmitted to the Earth's surface. Elsewhere, depending on ozone levels and cloudiness, transmission may drop to only 10 percent. However, even at high latitudes, summer exposures to UV-B differ little from those at the equator. The danger from UV-B is thus global, though annual exposures are likely to be greater nearer the equator.

Variations in ozone levels affect the amount of UV-B transmitted. A drop of total ozone concentration of 10 percent will increase UV-B radiation on the Earth's surface by some 20 percent.

UV-B can damage both proteins and DNA, the chemical that carries genetic information in living organisms. This may either cause the death of a cell, or alter the genetic message carried by the DNA. The latter process may result in two forms of cancer in man: localized skin cancers that usually respond to treatment and the more serious general skin cancer known as melanoma. Melanoma is much rarer but has a high mortality. Worldwide, about 10 000 people die from skin cancer every year.

There have been many studies of localized skin cancers in man. The disease is much more common among white people than among those with darker skins, and the figures that follow relate only to Caucasians who, in the United States and even without ozone depletion, stand a 12-30 percent chance of developing some form of non-melanoma skin cancer during their lifetime. Furthermore, the incidence of the disease is increasing, and there is an inverse relationship with latitude—skin cancer is more common nearer the equator than near the poles (*see Figure 16*). For example, one study showed that the rate of skin cancer in one area of Texas was 379 cases per 100 000 population per year but only 124/100 000 further north in Iowa. Overall in the United States there were about 300 000 cases of skin cancer a year in the 1970s, which means that between one-half and one-third of all cancers there are skin cancers. Figures are much lower

elsewhere: in the Soviet Union, skin cancers represent 15-26 percent of all cancers in the south and 9-14 percent in the north. Significantly, the rate of skin cancer is highest in Australia.

Several attempts have been made to try to estimate how increases in UV-B would effect rates of skin cancer. The best current estimate, though one that is still hedged with uncertainties, comes from the US National Academy of Sciences which estimates that each 1 percent depletion of ozone would increase the incidence of skin cancer by 2 percent. On this basis, a 3 percent reduction in the ozone layer would produce some 18 000 more skin cancer cases a year in the United States. Though such figures sound alarming, a similar result would occur if the population of the United States moved south by 2-3 degrees of latitude. Probably few people would regard such a move—rightly or wrongly—as a serious health hazard.

It is difficult to extrapolate such figures to the world as a whole because white people are much more susceptible to skin cancers—just as they are to sunburn—than are black people. Furthermore, it is possible to take precautions against the effects of increased ultraviolet radiation, simply by avoiding direct sunlight, particularly on parts of the body rarely exposed to it. One of the reasons for the current increase in rates of skin cancer is undoubtedly the growing fashion for sunbathing wearing few or no clothes. As much is confirmed by recent research which suggests that a 10 percent increase in UV-B would increase the incidence of melanomas in men by 8 percent on exposed parts of the body but by only 6 percent on parts of the body not normally exposed. In women, these figures are estimated at 10 and 5 percent respectively.

What the global toll in increased rates of skin cancer would be for different levels of ozone depletion cannot yet be estimated with certainty. In the United States, scientists have estimated that if CFC emissions were held constant, some 1.65 million cases of non-melanoma skin cancer could be prevented. The cost of such a moratorium, depending on the availability of alternative chemicals, is estimated at US$ 196-455 million.

Increased levels of UV-B would be likely to have many other effects on the human body, one of the most alarming of which is a tendency to suppress the efficiency with which the body's immune system functions. One reason why cancers are not more common in society than they already are is that the immune system is generally efficient at recognizing invading cancerous cells, and producing antigens to deal with them before they can become established. Research has shown that this mechanism works less efficiently when UV-B levels are raised. For the same reason, ozone depletion could increase the number of skin infections that occur, such as those caused by the herpes virus.

Although plants have developed protective mechanisms against high levels of UV-B, laboratory experiments show that plants vary widely in their response to increased levels of UV-B. So far, some 200 different plant species have been tested for UV-B sensitivity, and about two-thirds of them produced reactions. Sensitive species, such as cotton, peas, beans, melons and cabbage, grow more slowly and in some pollen fails to germinate. UV-B can damage plant hormones and chlorophyll, the chemical mainly responsible for photosynthesis. As a result, the rate of photosynthesis is often decreased and the total mass produced by the plant during a growing season correspondingly lowered. More specifically, prolonged trials with soy

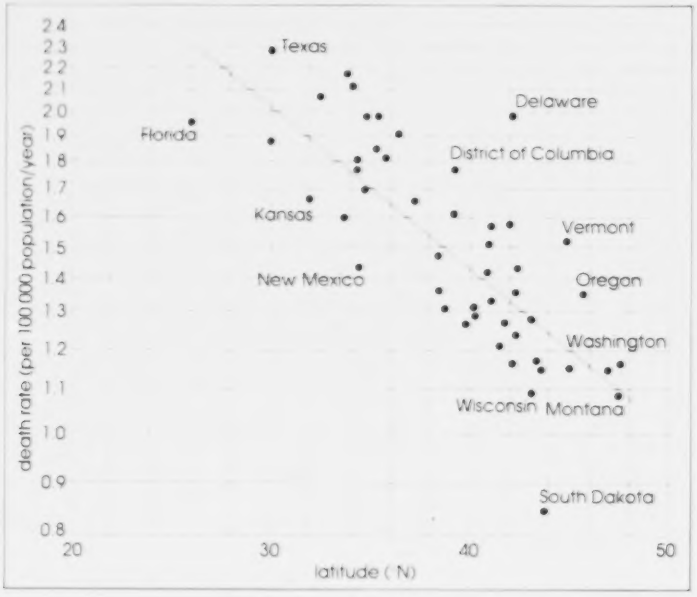


Figure 16 shows how death rates from one form of skin cancer —melanoma—vary with latitude. Death rates among white people are much higher nearer the equator

beans have shown that a 25 percent depletion of ozone levels would produce a 20-25 perecent drop in soy bean yields. It is thought that trees and grasses would also be severely affected by increased levels of UV-B. Severe damage to the ozone layer would thus be likely to result in reduced timber and crop yields.

UV-B can penetrate to considerable depth in clear water, and poses a particularly serious threat to single-celled algae. These are right at the top of the aquatic food chain, and if increased levels of UV-B led to severe damage among algae, the effects would be felt throughout aquatic ecosystems, perhaps leading to a decline in the populations of edible fish. There might also be a direct effect on fish larvae. Recent research shows that all anchovy larvae can be killed up to a depth of 10 metres by 15 days exposure to UV-B some 20 percent higher than current levels.

Much experimental work is currently in progress to quantify the relationship between increased UV-B and damage to plants and animals. While it is not yet possible to predict exactly how damaging a given increase in UV-B would be, there is no doubt that even a few percent reduction in the total ozone concentration would lead to effects that impaired human health, agriculture and possibly fisheries. Human populations and domestic stock would suffer increasingly from skin cancer and eye disease. Many domestic crops would produce lower yields, and timber production would fall. The effect on marine organisms is the least well understood, but there are widespread fears that the marine environment could undergo dramatic change because of the sensitivity of single-celled marine organisms to UV-B.

Finally, changes in future ozone concentrations would damage plant and animal life not only directly, but also indirectly. Higher temperatures coupled with increased low-level ozone concentrations would lead to more frequent and more severe smogs., for example. Furthermore, ultraviolet radiation is already responsible for the degradation of many common synthetic materials; it causes paints to fade, window glazing to yellow and car roofs to become chalky. Higher UV-B levels could increase these problems and damage many of the plastics currently used in the building industry and elsewhere. One recent study analysed the effect of a 2.5 percent annual increase in CFC production rates, leading to a 26 percent ozone depletion by the year 2075. By this time, damage to materials such as PVC would be substantial, and the cost of adding additional stabilizers to PVC to prevent the damage was estimated at about US$ 4.7 billion.

Effects of a changing climate

It is pointless to try to estimate the effect of changing ozone levels on climate without at the same considering the effects of changes in the concentrations of other gases in the atmosphere. Ozone, like carbon dioxide, is a greenhouse gas, as are many of the other trace gases that are currently influencing ozone distribution. When considering climate, these gases have to be treated as a system, and their roles in changing the concentrations of other gases and thus further influencing climate have to be considered as a whole. The best current estimates are that this system is likely to lead to a global warming by about 2030 of some 3 °C. What effects might this have on human society?

Such a warming of the Earth would be by no means trivial. A 1000 years ago, for example, the Earth was warmer than it is now, but by considerably less than 3 °C. Greenland earned its name then, for its green shores, though today it is an ice-covered island that would be better known as Whiteland. In the late Middle Ages, when the warming was even smaller, it was still sufficient to bring plagues of locusts to Switzerland.

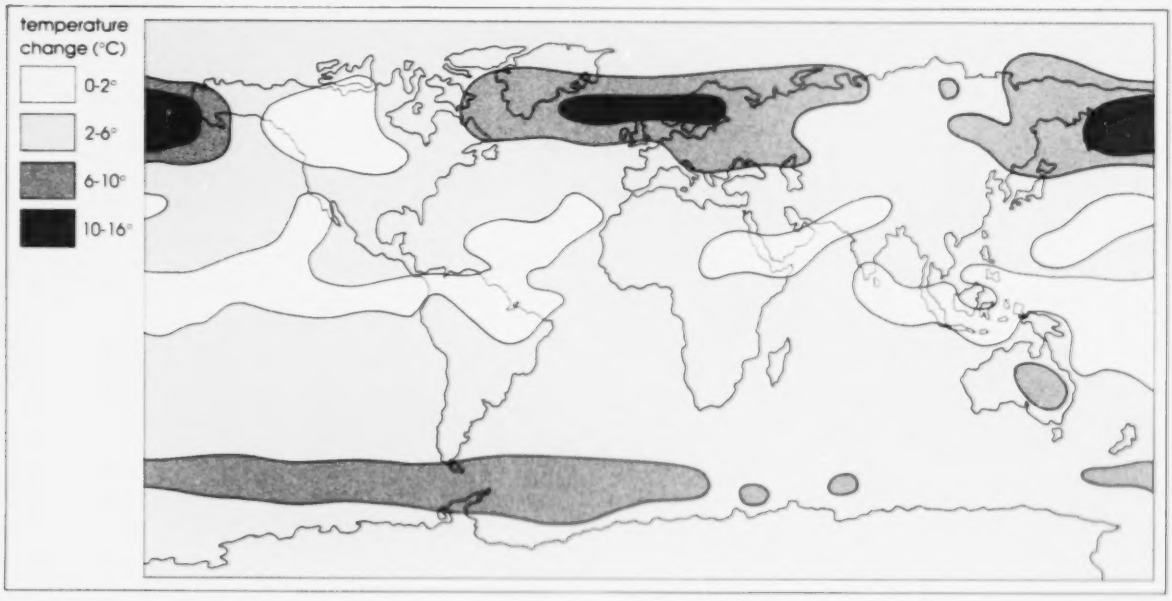
Furthermore, a global warming does not mean that the temperature would rise uniformly all over the globe. On the contrary, some areas would be likely to become very much warmer (*see Figure 17*). In the mid-latitudes, the warm season would be likely to lengthen, and the cold season to shorten. The warming would be more marked in the winter than in the summer, and annual temperature variations would therefore be reduced.

Some cities would undergo quite profound temperature changes. The effects of a carbon dioxide doubling on Washington DC, for example, have been analysed in some detail. The temperature in Washington currently exceeds 38 °C on an average of only one day a year; it exceeds 32 °C about 35 days every year. But, by the middle of the next century, these figures could rise to 12 and 85 days a year, making Washington a very much hotter place than it is now. Evenings would be hotter, too, because although the temperature fails to fall below 27 °C currently less than once a year on average, there would be as many as 19 evenings a year as hot as that in a climate in which carbon dioxide levels had been doubled.

As the atmosphere heated up, its capacity to hold water vapour would increase. Surface evaporation rates would therefore also increase, leading to more moisture in the atmosphere. Because water vapour is also a greenhouse gas, this would contribute to a further warming. Higher evaporation rates also imply that rainfall rates must increase to maintain equilibrium between the amounts of water vapour entering and leaving the atmosphere. However, rainfall rates would not alter uniformly across the globe—they would increase in some places and decrease elsewhere.

A general warming would also have complicated effects at the poles. Although snow and ice would tend to melt, there might initially be higher snowfall in very cold areas because of increased precipitation rates. However, as melting got under way, the reflectivity of the Earth's surface near the poles would decrease, and more radiation would be absorbed by the Earth. This would contribute to a further warming in high northern latitudes. The effect would be diminished in the Antarctic due to the seasonal break-up of pack ice there.

These are just a few of the known feedback mechanisms that would occur as a result of a global warming. Scientists have tried to model the behaviour of the Earth's climate as a result of a global warming, incorporating the effects of



these feedback mechanisms. The results appear broadly realistic, though what would happen at a regional level is still highly uncertain.

Most of these models indicate that precipitation would increase overall by some 7 to 11 percent. However, increased rates of evaporation would result in drier soils, in the mid-latitudes at least, and particularly in the Northern mid-latitudes in early spring. This has alarming implications for the germination of crops in the most important grain-growing region of the world.

One model indicates that soils would all be drier in North America, Siberia, southeastern South America, in the tropical rain forests and near the poles. Wetter conditions would prevail in most sub-tropical countries and west coast temperate zones.

Would the warming be sufficient to melt the polar ice? If the huge continental glaciers in Greenland and the Antarctic were to melt, one result would be a substantial increase in sea levels. Melting of the West Antarctic ice sheet alone would cause a rise in sea level of some 5 metres. This would have a major impact on human society, putting many ports out of action and leading to extensive flooding of low-lying areas. The removal of Arctic ice would also have enormous strategic and economic implications. However, with only one major exception, the models indicate that though polar ice would become thinner and less extensive, it would not disappear in the short term.

A slow rise in sea level is, however, a realistic possibility as a result of the thermal expansion of the oceans. It is estimated that a global warming of 1.5 to 5.5 °C would result in sea level increases of 20 to 165 cm respectively. By comparison, sea levels are estimated to have risen by between 5 and 19 cm during the 20th century. Because nearly one-third of all human beings live within 60 km of a coastline, significant sea level changes would have enormous effects on human society, causing mass migrations and major problems for coastal cities such as New York and Bangkok.

A number of specific studies have now been carried out to investigate these effects in more detail. They show, for example, that by the year 2100 in the United States between 20 and 55 percent of the US wetlands would be lost to the sea, with major implications for fisheries and the habitats of many different species. A 50-cm rise in sea level would have a severe effect on Egypt, flooding land in the Nile delta currently occupied by 16 percent of the nation's population.

Things would be much worse in Bangladesh, already highly vulnerable to flooding and the effects of tropical storms. Estimates suggest that a 50-cm rise in sea

Figure 17 Temperature changes predicted by one atmospheric model caused by a doubling of carbon dioxide. In winter, temperatures might rise by as much as 6-10 °C in parts of northern Europe

level would flood 12 percent of Bangladesh's land area; a rise in sea level of 2 to 2.5 metres would flood more than a quarter of that already densely populated land. In Bangladesh, as in many other developing countrties, much will depend on the results of work upstream to dam rivers and create hydroelectric power. Such dams serve to trap silt washed down by the river, making estuaries more vulnerable to flooding and rising sea levels.

The effects of all this on human society can only be hinted at. Increasing carbon dioxide concentrations, for example, tend to increase most crop yields. However, warmer average temperatures would almost certainly decrease maize and wheat yields in the mid-latitude regions of North America and Western Europe. One estimate is that a sudden warming of 2 °C would reduce average yields by 10 ±7 percent. While these effects are not particularly severe, more major changes might be difficult to combat in marginal food-producing areas where small changes in yield could have catastrophic consequences. For example, tropical forest land can currently be used for productive, sustainable agriculture only with difficulty. If the climate changed, the soil that supports tropical rain forests could well become even more unsuitable for agriculture.

A warmer and wetter climate would affect not just crop production but all aspects of human activity. Temperate forests would move towards the poles, energy needs change drastically, and world patterns of commerce undergo fundamental alterations. One study has investigated the 'cascade' effect that might occur as a result of a global warming. This was an analysis of the consequences in Canada's Southern Saskatchewan Province of the climatic changes predicted from an atmospheric model as a result of a doubling of carbon dioxide levels (which would produce an average global warming of some 3 °C).

The model predicted that there would be an increase of 3.4 °C in average temperature for the province and an 18 percent increase in precipitation. On the basis of yield variations resulting from anomalous weather conditions in the past, it was concluded that wheat production would fall by 25 percent, and farm incomes by 26 percent. Employment would fall 3 percent in the agricultural sector, and by 1.9 percent in the province as a whole. Household purchasing power would fall 12 percent.

Because man is continually adapting to a changing climate, the effects of a global warming would depend critically on the speed at which the climate changed: a sudden change would be much harder to combat than a slow one. Furthermore, it makes little sense to distinguish sharply between what might be called 'beneficial' as distinct from 'harmful' changes that result from a global warming. All types of climatic change require adaptations by human society, adaptations that generally take many decades to effect.

Implications for policy

The threat to the ozone layer is an unusual environmental issue. Unlike many other environmental problems, it potentially affects the well-being of every individual in every country. It is neither a developed country problem nor a developing country problem: it is a global problem.

Furthermore, the evidence that any real damage has yet occurred is very marginal—in contrast, for example, to environmental issues such as acid rain, coastal pollution, deforestation and desertification. It is thus possible that international action to safeguard the ozone layer could achieve an important first in environmental management: the effective control of a threat before any damage is actually done. For these reasons, UNEP has played a very active role in coordinating action to safeguard the ozone layer.

In 1977, UNEP convened a meeting of experts to draft the World Plan of Action on the Ozone Layer. The Plan called for a programme of research and assessment on the ozone layer and on the consequences that would occur should the layer be modified. UNEP's role was to coordinate and integrate this programme, and to do so it created a special body, the Coordinating Committee on the Ozone Layer (CCOL). By 1986, the CCOL had made eight separate assessments of the severity of the threat to the ozone layer in the light of new knowledge of atmospheric processes and trends in the release of chemicals into the atmosphere. In its 1986 report, the CCOL confirmed the threat to the ozone layer yet again, and made further predictions about the eventual levels of ozone depletion. In the same year, a special session of the CCOL also assessed the likely impact of these projected changes on man.

Continued concern over the years has led to increasing international acceptance of the need to take action to protect the ozone layer. UNEP therefore created a working group of legal and technical experts to frame a Convention for the Protection of the Ozone Layer which was adopted in Vienna by 21 states and the European Economic Community in March 1985 (though in early 1987 it had still to come into force). Several more states have since signed the convention (*see Figure 18*).

The 21 articles of the Convention pledge parties to protect human health and the environment from the effects of ozone depletion, and two annexes provide for participating states to cooperate in research, observation and information exchange.

Increased concern over the ozone layer has led several countries to regulate the production or the uses made of CFCs. For example, the United States banned the use of CFCs as aerosol propellants in 1978. A 1980 EEC Council Decision required EEC members not to increase production capacity of CFCs 11 and 12, and to achieve a 30 percent reduction in CFC use in aerosols by the end of 1981 compared to 1976. Individual countries such as Belgium and Portugal have in effect banned the production of CFCs altogether. The Netherlands requires aerosol cans to carry a warning of health and environmental risks related to CFC use. Denmark banned the use of fully halogenated CFCs in aerosols from 1987. Both Sweden and Norway operate a complete ban on CFCs for non-essential aerosol uses.

A Protocol to the Vienna Convention, on the Control of Chlorofluorocarbons, is being developed. The Protocol, involving a CFC production freeze followed by reductions in production by initially 20 percent, is expected to come into effect in 1988. A major problem is that annual production figures for the global production of these chemicals are not

accurately known. The Chemical Manufacturers Association makes available to UNEP and the CCOL data on the production of CFCs 11 and 12 from 21 major manufacturers in the United States, Canada, Europe, Japan, Brazil, Mexico, Australia and India. Although the Soviet Union is not a CMA member, that country has recently informed UNEP that its annual production capacity of CFC 11 and CFC 12 is 60 000 tonnes but its annual production depends on the level of trade with Eastern European countries.

Over the years, the urgency for international action to protect the ozone layer has increased. Although current models predict smaller depletion levels than those of a few years ago, these predictions are now held to be much more reliable. Indeed, over the past year or so, observational evidence has been produced that seems to confirm what in the past has been only theoretical speculation. This is an important turning point in our knowledge of what is happening to the atmosphere, and rapid advances can be expected in the near future. Because of the surprise discovery of the rapidly deepening ozone hole over the Antarctic, elaborate experiments to monitor trace gas concentrations in more detail from both satellites and aircraft are planned for the near future. This should both improve our understanding of what is going on and provide a means of refining current models of the atmosphere.

Recent results also pose new problems for policy makers. What, for example, are the implications of the discovery that ozone depletion is likely to be much more severe at high latitudes than elsewhere? This may require special action in those countries most at risk, particularly in the spring when the risk from increased UV-B is likely to be greatest. Similarly, the

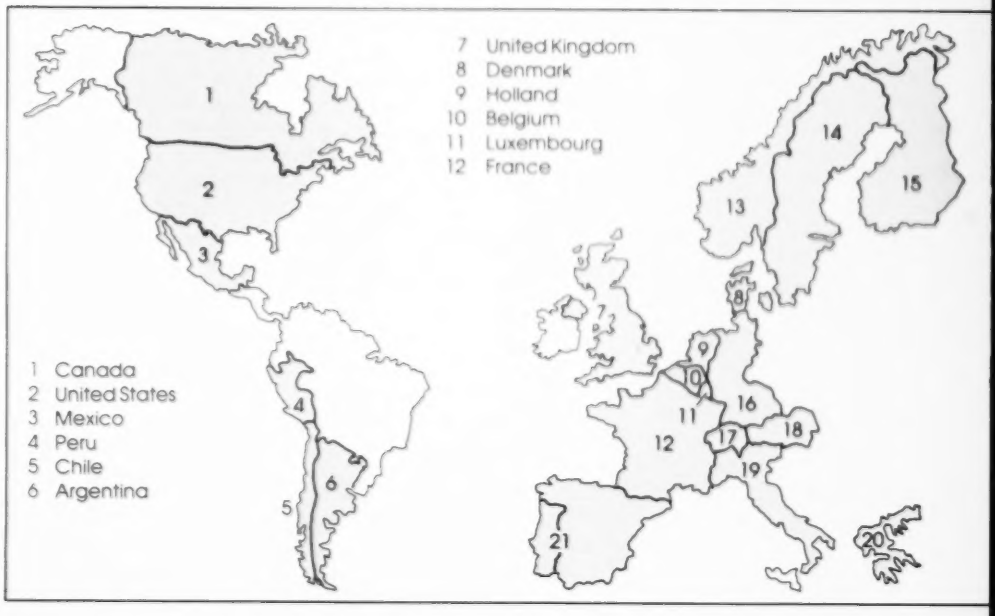
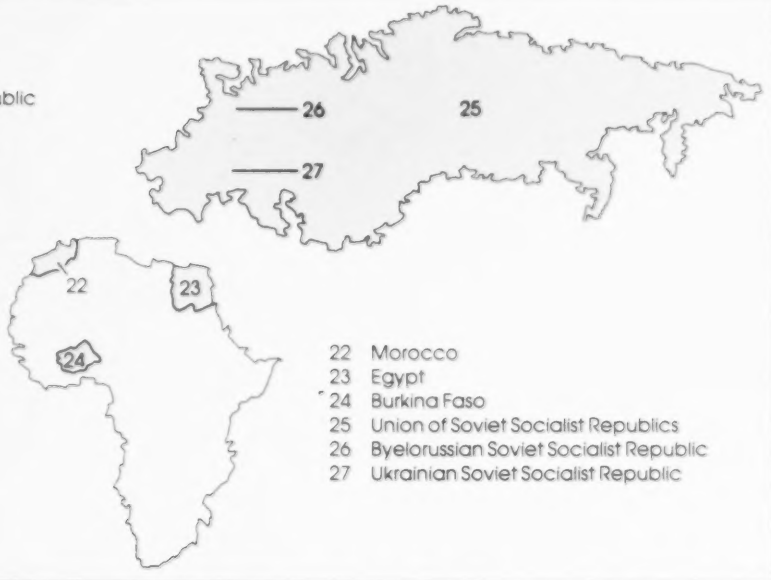


Figure 18 By the beginning of 1987, 27 countries had signed the Vienna Convention for the Protection of the Ozone Layer, which pledges signatory countries to protect human health and the environment from the effects of ozone modification, and provides for them to cooperate in research, observation and information exchange

global warming in which ozone will play a part now poses more realistic and urgent problems. One day, rates of fossil fuel combustion may well have to be tailored to limit the effects of climatic change. Because of the thermal lag of the oceans, such action might have to be taken decades ahead of the time when the expected climatic effects would occur.

Human society has little experience of dealing with problems on such a scale, and which might produce consequences of such dimensions. There is little doubt that the need to limit the incidence of UV-B on the Earth, and to keep climatic change to an acceptable minimum in the future, is already providing policy makers with totally new global responsibilities. It remains to be seen how effectively they will be able to cope with these responsibilities, and what new mechanisms they will be able to evolve to deal with them.



13 Norway
14 Sweden
15 Finland
16 Federal Republic of Germany
17 Switzerland
18 Austria
19 Italy
20 Greece
21 Other EEC countries

22 Morocco
23 Egypt
24 Burkina Faso
25 Union of Soviet Socialist Republics
26 Byelorussian Soviet Socialist Republic
27 Ukrainian Soviet Socialist Republic

Sources

Breuer, G. *Air in Danger: ecological perspectives of the atmosphere.* Cambridge, Cambridge University Press, 1980.

Inadvertent Climate Modification. Cambridge, Massachusetts, MIT Press, 1971, Report of the Study of Man's Impact on Climate.

International Council of Scientific Unions, United Nations Environment Programme and World Meteorological Organization. *Report of the International Conference on the Assessment of the Role of Carbon Dioxide and of other Greenhouse Gases in Climate Variations and Associated Impacts,* Villach, Austria, 9-15 October 1985. Geneva, WMO, 1986.

Kates, Robert W., with Ausubel, Jesse H., and Berberian, Mimi (eds.). *Climate Impact Assessment.* London, John Wiley, 1985 (SCOPE 27).

MacCracken, Michael C., and Luther, Frederick M. (eds.). *The Potential Climatic Effects of Increasing Carbon Dioxide.* Washington DC, US Department of Energy, 1985 (DOE/ER-0237).

NASA, US Federal Aviation Administration, NOAA, UNEP, WMO, Commission of the European Communities, Bundesministerium für Forschung und Technologie. *Atmospheric Ozone 1985: assessment of our understanding of the processes controlling its present distribution and change,* 3 vols. Geneva, WMO, 1986, Global Ozone Research and Monitoring Project Report No. 16.

National Academy of Sciences. *Halocarbons: environmental effects of chlorofluoromethane release.* Washington DC, National Academy of Sciences, 1975.

National Academy of Sciences. *Man-made impacts on the stratosphere.* Washington DC, National Academy of Sciences, 1975.

Seidel, S., Tirpak, D., and Hoffman, J. S. *Potential health and environmental effects of ozone depletion and climate change.* Paper prepared for UNEP workshop on Protecting the Stratospheric Ozone Layer, Leesburg, Virginia, September 8-12, 1986.

Titus, James G. (ed.). *Effects of changes in stratospheric ozone and global climate: Volume 1, Overview.* Proceedings of the International Conference on Health and Environmental Effects of Ozone Modification and Climate Change, 16-20 June 1986. Nairobi and Washington DC, United Nations Environment Programme and United States Environmental Protection Agency, 1986.

Tromp, S. W. *Biometeorology: the impact of the weather and climate on humans and their environment.* London, Heyden, 1980.

United Nations Environment Programme. *Report of the Eighth Session of the Coordinating Committee on the Ozone Layer,* Nairobi, Kenya, 24-28 February 1986. Nairobi, UNEP, 1986.

United Nations Environment Programme. *Possible Effects of Man's Activities on the Ozone Layer and Climate.* Nairobi, UNEP, 1986, UNEP Policy Support Document.

Watson, R. T., Geller, M. A., Stolarski, R. S., and Hampson, R. F. *Present State of Knowledge of the Upper Atmosphere: processes that control ozone and other climatically important trace gases.* NASA, Washington D.C., 1986, NASA Reference Publication 1162.